

Performance analysis of WDM MIMO RoFSO links for 5G applications

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ABSTRACT

The soon to be deployed 5G systems are expected to cater an agglomerate of services at profuse data rates wirelessly. Radio over fiber (RoF) networks are the most suitable to implement such systems. In situations where the practical implementation of RoF systems are non-viable, radio over free space optical (RoFSO) links can be employed. The traditional wavelength division multiplexing (WDM) technology can be incorporated to multiply the data rates. However, the link performance may be degraded due to various atmospheric factors. This can be compensated using multiple input multiple output (MIMO) techniques. In this paper, the performance analysis of such a WDM RoFSO link for 5G frequencies is carried out. The work also presents quantitative performance comparison between single input single output (SISO) and MIMO RoFSO links for 5G systems which will be useful for researchers in this area. It is observed that, while WDM provides additional data capacity, it degrades the link performance under adverse weather conditions which can be counterbalanced using MIMO techniques.

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1. INTRODUCTION

The ever increasing need for high bandwidth has forced the wireless communication systems to restructure their architectures to adapt to the new standards. The available 4G networks are almost saturated and cannot accommodate the wide range of services in demand [1]. The deployment of the fifth generation networks, which promises a line-up of services with exceptional data rates, is brewing around the globe [2]. Upgrading to 5G networks brings about new communication standards and infrastructure requirements. Additional high frequency bands are required to serve multiple services with high bandwidth [3], [4]. The use of higher frequencies will decrease the cell sizes, thereby increasing the overall system cost due to the necessity of large number of base stations or radio access points (RAP) [5], [6]. To realize such a complex network consisting of high and low frequency bands, radio over fiber (RoF) is an appropriate architecture.

RoF is a composite technology which comprises optical and wireless communication links [7], [8]. In contrast to traditional optical networks where baseband data is transmitted using light, RoF systems transport radio frequency (RF) signals. This simplifies the base station architecture considerably and reduces the total system cost [9]-[11]. This enables the large-scale deployment of the system with a large number of base stations for providing high frequency bands. The RoF networks are highly straightforward and can be used to transport any analog/digital signals irrespective of modulation, frequency bands, and services for which they are used. However, as a wired network till the base stations/RAPs, practical difficulties may arise

in laying the optical fiber cable in certain scenarios. In such circumstances, an alternative version of the RoF termed as radio over free space optics (RoFSO) can be used [12], [13].

RoFSO links use free space/atmospheric channel for communication and omits the trouble of deploying fiber cables. The links basically require a set of transceivers placed at the line of sight to enable communication [14], [15]. This enables fast deployment and possesses a lot of potential advantages and applications. No spectrum licensing, high throughput when combined with wavelength division multiplexing (WDM), immunity to interference, security, reduced costs and maintenance are some of the advantages of the system [16]. The applications include scenarios where trenching is impossible or when temporary installations for emergency situations like disaster management are needed. It can also be used to set up metropolitan area networks (MAN), local area networks (LAN), and back-haul networks [17]. However, since the link uses atmospheric channel, the link performance highly depends on climatic conditions like rain, and fog. Light beam dispersion, shadowing, atmospheric pollution and absorption are some of the other restraining factors [18], [19]. The effects of these unfavorable conditions can be mitigated using multiple input multiple output (MIMO) transceivers [20]-[24].

WDM is a proven technology used in optical fiber networks to expand the capacity of the system [25]. In WDM, multiple wavelengths carrying different data are transported simultaneously through a single fiber. By incorporating the WDM technique into RoFSO systems, the data carrying capacity of the links can be further increased [14]. The transparency to signals and potential for high throughput makes it an appropriate candidate for the last mile deployment of 5G networks. The basic structure of a RoFSO link is depicted in Figure 1.



Figure 1. Basic structure of a radio over free space optical link

A lot of research has been carried out in connection with free space optical (FSO) systems. Various techniques were proposed to maximize data capacity, to tackle the ill effects of environmental factors, and to minimize the cost [26]-[28]. However, the feasibility and analysis of RoFSO systems for 5G applications introducing the 26 GHz high frequency band was not yet studied. The possibilities of incorporating WDM to RoFSO systems also were not fully worked out. This paper concentrates on analyzing such a WDM RoFSO link. It also emphasizes a comparison between single input single output (SISO) and MIMO WDM RoFSO links. The paper is organized into four sections with section 2 describing the system design and parameters used in the work, section 3 providing the analysis and comparison, and section 4 concluding the work.

2. RESEARCH METHOD

The simulation configuration of an 8 channel WDM RoFSO system employing 4×4 MIMO is depicted in Figure 2. The setup uses eight individual continuous wave (CW) laser sources to produce eight wavelengths. The eight wavelengths considered in this work are 1544 nm, 1546 nm, 1548 nm, 1550 nm, 1552 nm, 1554 nm, 1556 nm, and 1558 nm. A wide wavelength spacing is chosen so as to study the effect of wavelength on the link. The comparison carried out is among SISO, 2×2 and 4×4 MIMO layouts of 8 channel WDM RoFSO system. The SISO link equips a single transmitter (Tx) at the transmitting end and a single receiver (Rx) at the receiving end. The 2×2 and 4×4 MIMO links use 2 and 4 transceivers respectively. However, the optical power emitted from a single transmitter, 2 transmitters, and 4 transmitters are maintained equal for an unbiased analysis. This is achieved using optical power splitters which chop the input power equally into desired number of outputs. Optical power combiners are used at the receiver to combine the light inputs received from different paths.

As shown in Figure 2, an 8 channel WDM RoFSO link carrying 10 Gbps random data per channel is considered for the study. The light power output of each laser is set to be 1 mW (0 dBm). Pseudo random bit sequence generators (PRBS) are used to generate the random data for experimentation. A sequence length of 1024 bits at 64 samples per bit is selected. The generated random bits are non-return to zero (NRZ) coded using dedicated converters. The coded data is then modulated on to the 26 GHz 5G RF band. Instead of the low frequency sub 6 GHz bands, 26 GHz high frequency band is selected to analyze the RoFSO system performance in small cells at high data rates [29]. To keep the system simple and devoid of any modulation effects, on-off keying (OOK) is used to modulate data on RF signals. The reference wavelength chosen for

the study is 1550 nm. These parameters are set globally and are kept unvarying for all simulations for fair comparisons.

The data modulated 26 GHz RF signals are modulated on to light using single drive mach-zehnder modulators (MZM). In lieu of the simple direct laser modulation, external modulation using MZM is preferred to accommodate higher data rates. The RF modulated light signals are then combined together to form a single stream of light using a WDM multiplexer. The eight channel WDM multiplexer flocks together all the eight wavelengths which are already modulated with eight individual RF signals. The combined light output of the multiplexer is amplified using an optical amplifier. The optical amplifier magnifies the signal power by 20 dB. An ideal optical amplifier is considered in this study to avoid the effects of amplifier noises. The boosted light signals are then transmitted using the transmitter assembly (Tx).

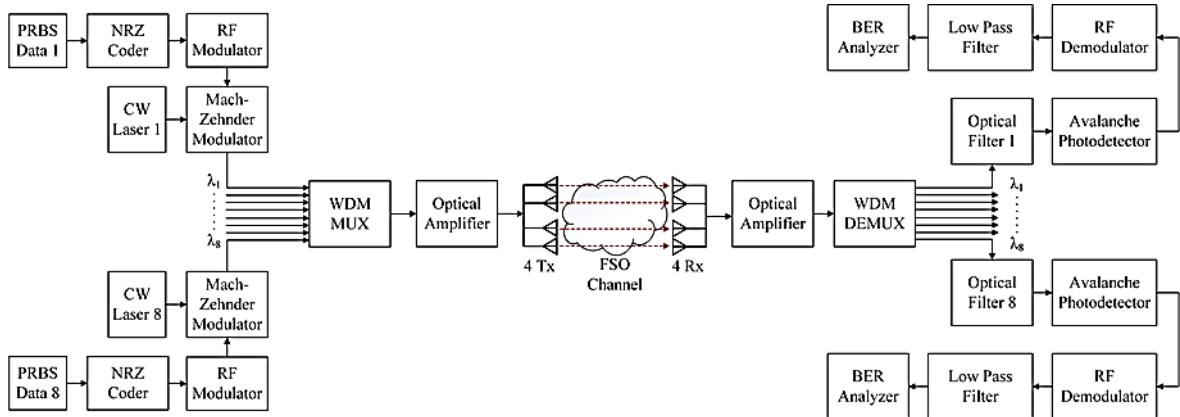


Figure 2. Simulation setup of an 8 channel WDM 4x4 MIMO RoFSO communication link

At the receiver, a lens based assembly is used to collect the light signals. The gathered light which is feeble in power is amplified using an ideal optical amplifier which provides a 20 dB gain. The amplified light signals are split into individual wavelengths using a WDM demultiplexer. Gaussian optical filters are used to filter the separated wavelengths from unwanted wavelengths. The optical filters used are centered at the corresponding wavelengths with a bandwidth of 55 GHz which is wide enough to include the sidebands of a 26 GHz RF signal. An avalanche photodiode (APD) is used to detect the filtered optical signals. The selected APD provides a gain of 3, responsivity of 1 A/W, and has a dark current of 10 nA. The electrical RF signal output of the APD is amplitude demodulated using an AM demodulator. The AM demodulator extracts the data from the RF signal. An additional Bessel lowpass filter is used to filter the demodulator output. The filtered data is then correlated with the transmitted data using a bit error rate (BER) analyzer and the number of error bits per number of transmitted bits is assessed [30].

The link performance analysis is carried out by varying the transmission range. Losses of 1 dB each is granted for transmitter and receiver. The beam divergence is assumed to be 2 mrad. To account for the geometrical loss of the transceiver, transmitter and receiver aperture diameters are chosen as 10 cm and 45 cm, respectively. Among the various models available for the characterization of the atmospheric channel, gamma-gamma model is used in this study. The light power P_r at the receiving end is calculated as:

$$P_r = P_t \frac{d_r^2}{(d_t + \theta L_p)^2} 10^{\frac{-\alpha L_p}{10}} \quad (1)$$

where P_t is the transmitted light power, d_r is the aperture diameter of receiver in meters, d_t is the aperture diameter of transmitter in meters, θ is the beam divergence in mrad, L_p is the path length, and α is the free space attenuation [31]. The atmospheric channel attenuation α is primarily governed by climatic conditions and the transmission wavelength. The attenuation α is estimated as:

$$\alpha = \frac{3.91}{\nu} \left(\frac{\lambda}{\lambda_0} \right)^a \quad (2)$$

where v denotes visibility in km, λ specifies the transmission wavelength in nm, and q refers to the attenuation producing atmospheric particle size distribution. A reference wavelength of 550 nm is fixed as reference wavelength λ_0 for computing attenuation [32].

The Kruze model selected in this study for channel modelling prescribes $q = 1.6$ for $v > 50$ km, $q = 1.3$ for $50 \text{ km} < v < 6$ km, and $q = 0.58 v^{1/3} + 0.34$ for $v < 6$ km. The (2) is used to estimate the attenuation for various atmospheric conditions. The attenuation in decibels τ , can be calculated as, $\tau = 4.3429 \times \alpha \times L$ where L is transmission range [32]. For the study conducted, the weather is assumed to be clear sky with minimum attenuation. As per the Kruze model, the visibility for clear sky is assumed around 23 km. The attenuation for this condition can be calculated using (2) as 0.2 dB/km for 1550 nm wavelength. It can be seen that the attenuation value is almost similar to the attenuation of a standard optical fiber. This attenuation is used for all models evaluated in this work.

In this work, a quantitative performance analysis and comparison is carried out using BER and Q-factor as metrics. For an ideal optical communication system, the BER value is expected to be less than 10^{-9} and Q-factor above 6. A BER of 10^{-9} signifies one bit error per 10^9 bits dispatched, and the analogous Q-factor for this case is 6. Q-factor is simply the ratio of difference between the mean values of received signal levels to the sum of standard deviations of noises at the levels. Q-factor directly points to the signal to noise ratio of the received signal. The link performance is analyzed by varying the transmission range from 0 to 2.5 km.

3. RESULTS AND DISCUSSION

For performance analysis and comparison, iterations were made on the transmission range, and the performance metrics BER and Q-factor were evaluated. The link is analyzed up to a distance of 2.5 km beyond which the BER of the links were more than the acceptable level of 10^{-9} . All the eight pseudo random data sources were running at 10 Gbps each. The eight distinct wavelengths 1544 nm, 1546 nm, 1548 nm, 1550 nm, 1552 nm, 1554 nm, 1556 nm chosen were centered around the 1550 nm reference wavelength. The optical power output of each laser was set at 1 mW (0 dBm). For system performance assessment, the input and output bits are correlated and the number of errors were calculated. A comparison among the three WDM RoFSO models used in this study viz. SISO, 2×2 MIMO and 4×4 MIMO were also carried out in terms of BER and Q-factor.

The traditional WDM technology is incorporated to all the architectures tested here to increase the capacity of single channel RoFSO system. The 8 channel WDM setup is evaluated with SISO, 2×2 MIMO, and 4×4 MIMO RoFSO links. The range vs BER performance of an 8 channel WDM SISO RoFSO link is depicted in Figure 3(a). From the plot, it can be understood that beyond 1 km, the link is unable to offer an acceptable BER level of less than 10^{-9} . The link performance in terms of quality factor is also plotted in Figure 3(b). It can be seen that the Q-factor runs below the satisfactory level of 6 for distances greater than 1 km.

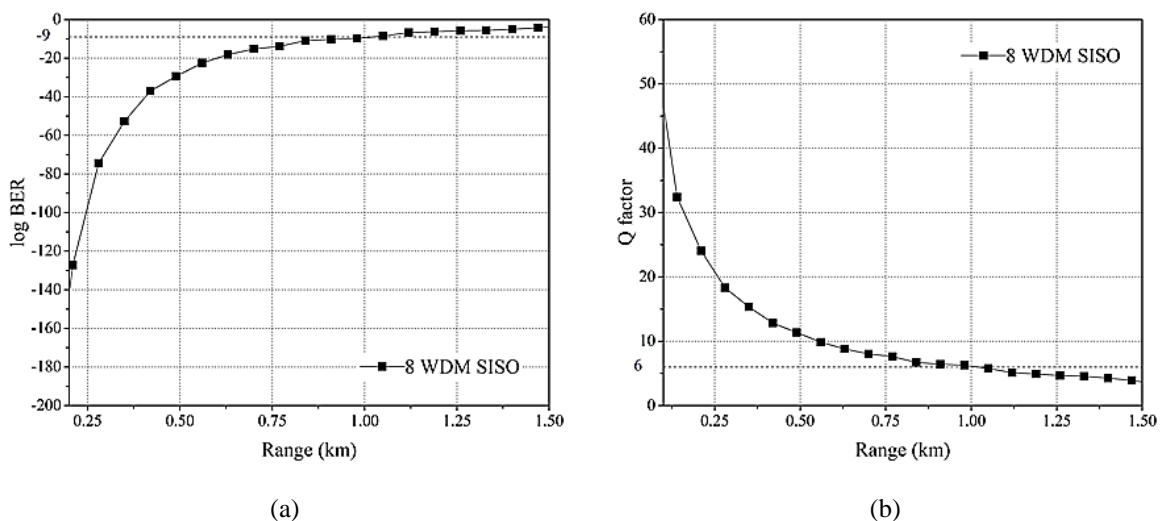
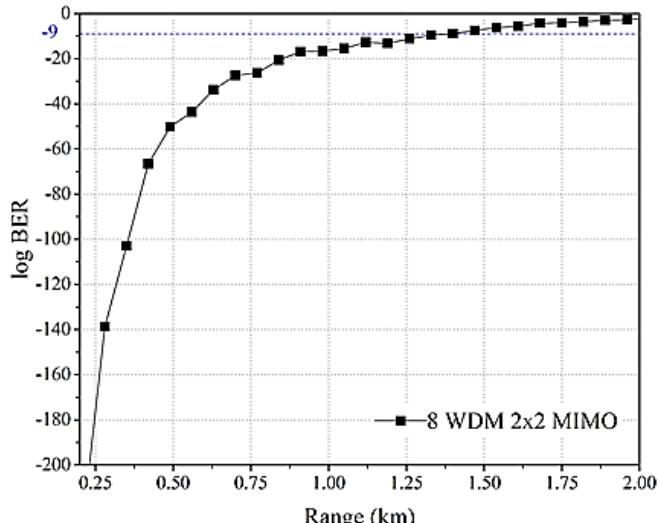
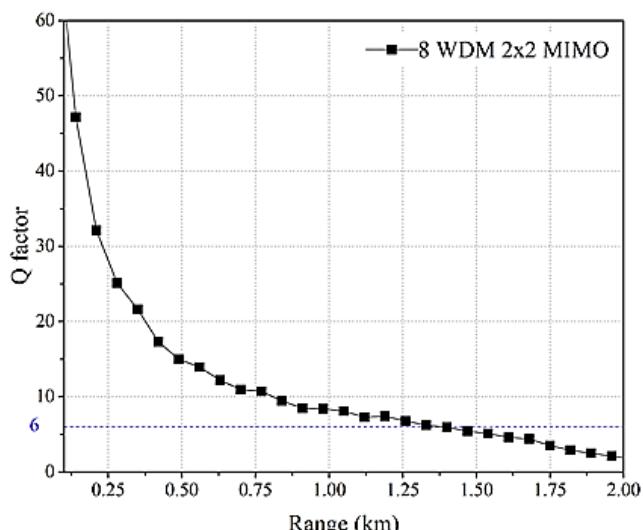


Figure 3. Performance of an 8 channel WDM SISO RoFSO link: (a) range vs BER and (b) range vs Q-factor

Similarly, the range vs BER plot of an eight channel WDM 2×2 MIMO RoFSO link is given in Figure 4(a). From the Figure 4, it is evident that the link provides a satisfactory BER of 10^{-9} up to 1.3 km. Figure 4(b) gives the range vs Q-factor performance of the same link. The Q-factor metric also points that the link is efficient only up to 1.3 km providing a Q-factor of 6.



(a)



(b)

Figure 4. Performance of an 8 channel WDM 2×2 MIMO RoFSO link: (a) range vs BER and (b) range vs Q-factor

An 8 channel WDM 4×4 RoFSO link was also analyzed and its range vs BER performance is illustrated in Figure 5(a). From the figure, it can be identified that the link is capable of achieving an acceptable BER of 10^{-9} upto 2 km. The range vs Q-factor performance plotted in Figure 5(b) also suggests the same 2 km distance upto which the link produces a Q-factor greater than 6.

For a better understanding of the link performance and effect of introduction of MIMO technique, a comparison of the three layouts in terms of BER and Q-factor is also plotted in Figure 6. From the figure it can be deduced that the link performance increases when the number of transceivers increases. Out of the

three architectures considered, it is clear that the 4×4 MIMO link provides superior performance. By analyzing the trend, it can be deduced that an increase in the number of paths using more number of transceivers can increase the link performance. It has to be noted that this boost in performance is achieved without increasing the power transmitted. The link effectively delivered 8×10 Gbps data up to 2 km using 4×4 MIMO setup.

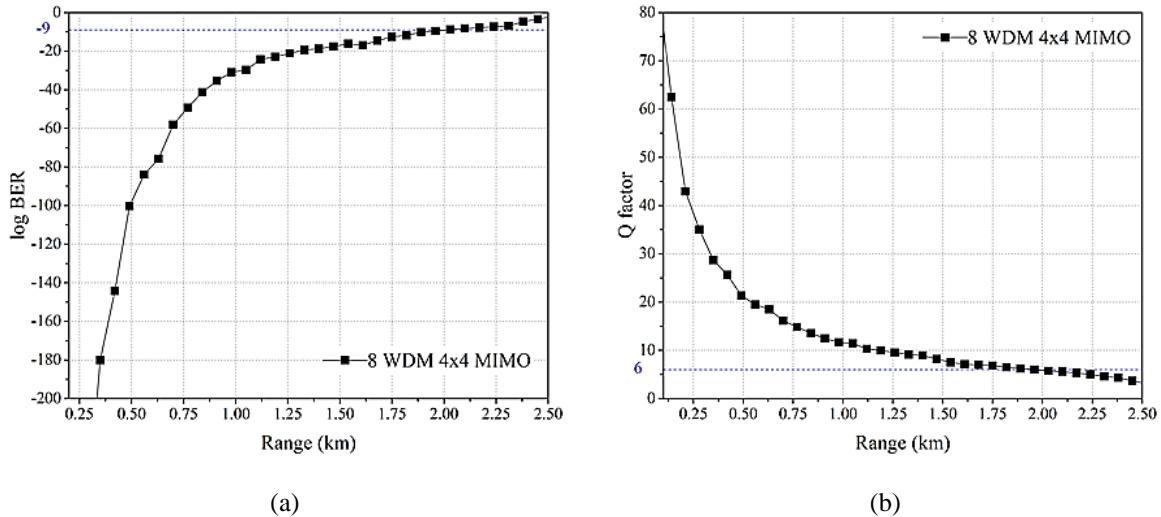


Figure 5. Performance of an 8 channel WDM 4×4 MIMO RoFSO link: (a) range vs BER and (b) range vs Q-factor

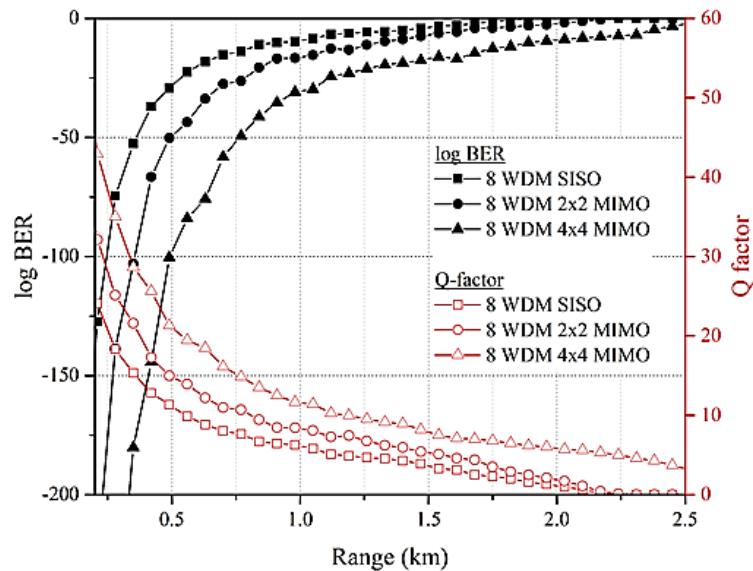


Figure 6. Performance comparison of 8 channel WDM SISO, 8 channel WDM 2×2 MIMO, and 8 channel WDM 4×4 MIMO RoFSO links

4. CONCLUSION

Performance analysis and comparison of WDM RoFSO links were conducted in terms of BER and Q-factor. Though the MIMO techniques were expected to provide better performance, their effects were not validated in the 26 GHz band 5G frequencies. In this work, it is established that the use of MIMO technique helps to improve the transmission range and overall link performance of WDM RoFSO links. While the range of SISO link was limited to 1 km, the 2×2 and 4×4 MIMO links were able to perform satisfactorily upto 1.3 km and 2 km respectively. The 4×4 MIMO link successfully transported 8×10 Gbps data over 2 km

distance. Such networks employing multiple transmitters and receivers can enable high capacity communication for 5G applications. We hope that this work will be helpful for researchers in this field for comparative studies. The possibility of further increase in link performance can be studied by employing advanced modulation schemes.

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